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A study on the effectiveness of eggshell as an abrasive agent in toothpaste

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ABSTRACT

Growing concerns about the safety of synthetic ingredients in dental products have led to the search for natural alternatives. This study explores the potential of using eggshell as a calcium-rich byproduct of the food industry as a sustainable toothpaste ingredient. Eggshell powder, with its high content of calcium carbonate, was used in addition to a toothpaste base and its physicochemical properties were analysed using FTIR, XRD, and XRF. The formulated toothpaste was then tested for % calcium content, pH, foaming ability, and abrasiveness, with results compared to a commercial toothpaste. The eggshell-based toothpaste had 93.51 % calcium, a slightly alkaline pH of 8.05 and produced 14 mL of foam. The value was roughly 16.7 % more than that produced by the commercial one, which was 12 mL. Its moderate abrasiveness mimics the cleaning performance of conventional formulations, which suggests safe and effective cleaning performance. These results demonstrate that the eggshell powder can be used as a viable and eco-friendly alternative to synthetic fillers in toothpaste that would have functional properties while helping to reduce waste from the food industry.

1. INTRODUCTION

The synthetic abrasive agents that are mostly used in commercial toothpastes include hydrated silica, calcium carbonate, and aluminum hydroxide. Even though these agents are effective in removing dental plaque and surface stains, their prolonged usage and long-term presence of chemical compounds cause justifiable questions about the safety, cost, and environmental sustainability (Lugo-Flores et al., 2021;

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Mayta-Tovalino et al., 2022). The growing demand of eco-friendly tooth care products has therefore triggered the exploration of natural and biodegradable options that can provide similar levels of cleaning power.

Eggshell waste which is generated in large amounts by the food industry and households is a renewable source of calcium carbonate ($CaCO_3$), and it is approximately 94 – 97% of the composition (Abou Neel & Bakhsh, 2021). Another structural component that makes the eggshell hard and strong is the presence of trace minerals like magnesium and phosphorus, among others (Onwubu et al., 2019). Eggshell powder is fine and mineral-rich and when properly cleaned and worked results in a fine abrasive with little negative effect on the environment. It also facilitates remineralisation of the enamel of the teeth, which might have some beneficial effects on oral health as compared to synthetic products. The use of eggshell waste is also congruent with the principles of the circular economy since it transforms the food waste into a useful material (Casinillo et al., 2024; Kumar et al., 2022).

Irrespective of these strengths, very little research has been specifically carried out to deal with abrasiveness, pH stability, and foaming properties of eggshell-based toothpaste formulations. The rigidity of the eggshell particles should also be strictly regulated to guarantee efficient cleaning without compromising the integrity of the enamel (Cheng et al., 2020). Furthermore, another essential parameter is pH and foam formation, which affect the stability of the formulation and user experience (Gavic et al., 2018; Hassan & Moharam, 2023). A balanced pH is necessary to inhibit enamel erosion, whereas sufficient foaming increases the distribution of toothpaste and its capacity to be perceived to clean the teeth effectively during brushing (Carolina et al., 2020). To this end, these parameters need to be systematically assessed to support the safety and effectiveness of toothpaste made of eggshells.

Eggshell waste application is a low-cost and viable long-term solution to the formulation of oral care products. Because Malaysia relies on imported toothpaste, the valorisation of the local eggshell waste would decrease production and encourage local innovation in the personal care field (Anis et al., 2019). Natural toothpastes, which already include clove, aloe vera, and neem extracts, have already received consumer preference because of their biocompatibility, as well as low cytotoxicity (Kanouté et al., 2022). On the same note, toothpaste, based on eggshells, may also provide a cheap, safe, and eco-friendly option to oral health care.

Thus, the proposed research project will compare the promise of eggshell-generated calcium carbonate as an abrasive component in toothpaste products. The viability and usefulness of the developed toothpaste is evaluated based on the abrasiveness, pH, and foaming capabilities of the developed toothpaste and thus, gives some understanding of the effectiveness of the product in terms of performance and sustainability as a substitute for the traditional synthetic formulations.

2. METHODOLOGY

2.1 Materials

Waste eggshells were collected from houses and local restaurants. The chemical ingredients for toothpaste preparation, including sodium fluoride, sorbitol, sodium dodecyl sulphate, methylparaben,

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sodium benzoate, and xanthan gum, were purchased from BT Science Sdn Bhd, Malaysia. Peppermint oil was bought from SNJ Chemicals Mart, Malaysia.

2.2 Methods

Preparation of eggshells from food waste

The waste eggshells were thoroughly washed with water to remove dust, impurities, and organic matter adhering to their surface. Subsequently, they underwent several cleanings with distilled water. Following this, the eggshells were dried in an oven at 150 °C for one(1) hour (Gautam et al., 2020). The dried eggshells were crushed into a coarse powder using a blender, and the fine powder was collected through 100 µm size sieving. Afterwards, the eggshells were calcined in the furnace. Once cooled, the resulting eggshell powder was stored in a desiccator for 24 hours to remove any remaining moisture. Following this, the dried powder was transferred to an airtight container labelled for storage. Fig. 1 shows the process flow of eggshell powder preparation. Then, some eggshell powder was calcined in a muffle furnace under an air atmosphere at 900 °C for one(1) hour with a heating rate of 10 °C/min (Ahmad et al., 2021).

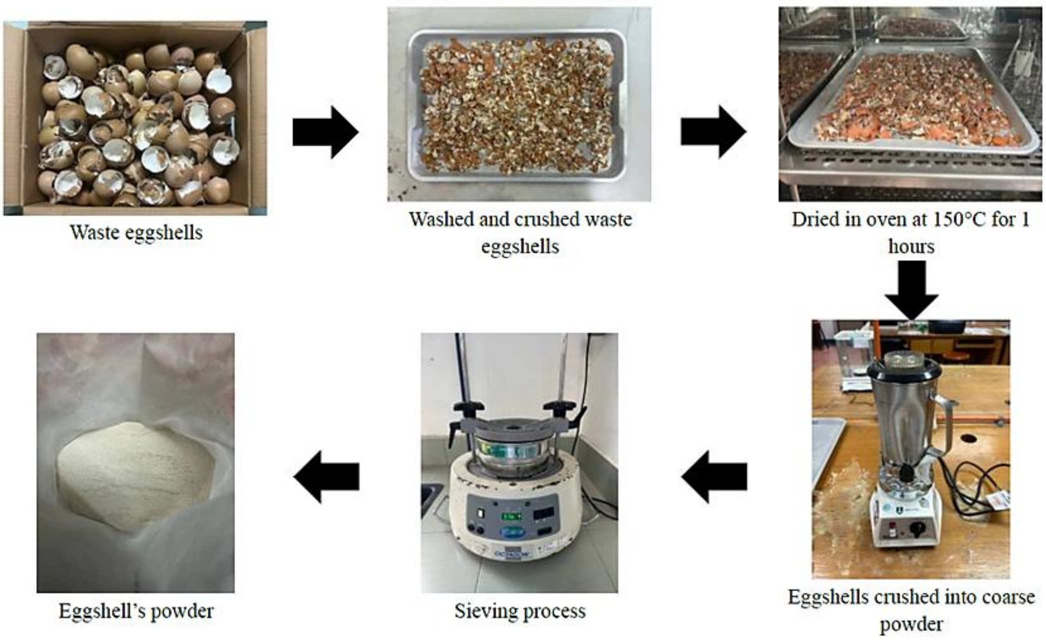

Fig. 1. Preparation of eggshell powder

Source: Author's illustration

Procedure on formulation of eggshell-based toothpaste

The toothpaste preparation involved the utilisation of various components. Based on Table 1, eggshell powder ($CaCO_3$) served as the primary abrasive for effective cleaning, with around 30 % of the total weight. Additionally, an anti-caries agent was added to prevent tooth decay. The formulation included sorbitol as

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a binding agent, sodium dodecyl sulphate acting as a surfactant and foaming agent, preservative agents such as methylparaben and sodium benzoate, xanthan gum as a sweetening agent, and peppermint oil for flavouring pleasant taste and aroma (Patel et al., 2025).

Table 1. Composition for the ingredients in toothpaste base

No	Ingredients	Quantity (%)	Uses
1.	Raw Eggshell Powder ($CaCO_3$)	30.00	Abrasive
2.	Sodium Fluoride	0.15	Anti carries agent
3.	Sorbitol	20.00	Humectant and binding agent
4.	Sodium Dodecyl Sulphate	1.50	Surfactant and foaming agent
5.	Methyl Paraben	0.25	Preservative
6.	Sodium Benzoate	0.50	Preservative
7.	Xanthan Gum	0.75	Sweetening agent
8.	Peppermint Oil	1.00	Flavouring
9.	Water	45.85	Diluent

Source: Author's own data

Using the Dry Gum Method, the solid ingredients were accurately weighed as per the specified formula and subsequently ensured uniform particle size. These materials were then combined in a mortar and pestle and triturated thoroughly with accurately weighed sorbitol until a semisolid mass was formed as shown in Fig 2.

a)

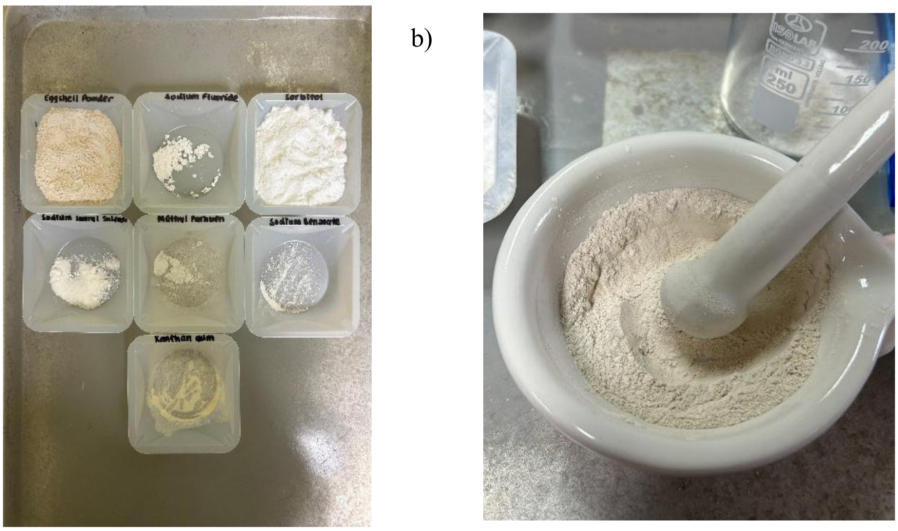

Fig 2. (a) Preparation of eggshell based toothpaste ingredient and (b) mixing of ingredients in mortar.

Source: Author's illustration

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Qualitative analysis of calcinated eggshell powder

The calcined samples were then characterised by FTIR, XRD and XRF. The composition of calcinated eggshell powder was being examined using FTIR, where the eggshell was first being turned into a fine powder for consistency. Potassium bromide (KBr) was then being mixed with this powder and pressed into a pellet. The spectral data of the powder in the mid-infrared range was being recorded by the FTIR instrument.

The crystalline nature of eggshell powder was being investigated through XRD. A thin, even layer of the powder was being placed on a substrate and inserted into the XRD instrument at 35 kV and 30 mA, scanning over a 2θ range of 20° to 90° at a speed of 2°/min. The instrument was scanning the sample, producing a diffraction pattern that displays its crystalline structure.

Analysis of composition in calcined eggshell powder and eggshell-based toothpaste

XRF spectroscopy was employed to determine the elemental composition of the calcined eggshell powder and the eggshell-based toothpaste, to identify compositional changes after formulation. In this analysis, the sample was exposed to high-energy x-rays, which cause the atoms within the sample to emit secondary (fluorescent) x-rays. The energies and intensities of these emitted x-rays were measured by the XRF spectrometer.

Analysis of the effectiveness of eggshell-based toothpaste

For the abrasion test, one gram each of eggshell-based toothpaste was prepared. Aluminium foil was used as the test surface, which aluminium foil was cut to 10 × 10 cm dimensions. Then, toothpaste was rubbed on aluminium foil with consistent pressure for 2 minutes. Tissue paper was used to wipe clean the aluminium foil to observe the visual inspection before and after the test, such as scratches or dullness, which is a sign of abrasion. The results were recorded and compared to evaluate the effect of abrasiveness for eggshell-based toothpaste.

In pH analysis, the pH of each sample was measured using a benchtop pH meter with a glass electrode at 25 °C. The reading was taken three times, and the average pH value was recorded. The samples were prepared in a 20 mL glass vial by diluting the toothpaste in distilled water at a ratio of 10 to 1 (Gavic et al., 2018). Then the slurry toothpaste was mixed on a hot plate using a magnetic stirrer at 25 °C for 10 minutes. The pH electrode was immersed in a stirred sample solution to ensure full contact with the slurry. The sample was continuously mixed to maintain uniformity. After each measurement, the electrode was rinsed with distilled water and acetone. It was then dried with Kimwipes to remove any residue. The test was repeated several times to obtain the average pH value.

About two (2) grams of each toothpaste sample was weighed. Each sample was mixed with 20 mL of distilled water in a beaker. The mixture was stirred with a glass rod for two(2) minutes to produce foam. The foaming properties of commercial and eggshell-based toothpaste were then compared. The resulting foam solutions were then poured into graduated cylinders and allowed to settle briefly to stabilise. The height of the foam in each cylinder was measured and recorded. Foam height and stability were analysed as indicators of foaming efficacy between the two toothpaste formulations.

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3. RESULTS AND DISCUSSION

3.1 Model and quantitative analysis of calcined eggshell and eggshell-based toothpaste

The eggshell-based toothpaste formulation from this study was analysed qualitatively through a series of analysis in FTIR and XRD. The quantitative analysis using XRF was focused on the percentage of calcium content in eggshell and toothpaste formulation. The results are reported here.

Fourier transform infrared spectroscopy (FTIR)

The qualitative analysis of eggshell powder using FTIR as shown in Fig. 3 reveals the characteristic absorption bands corresponding to various functional groups present in the sample. The prominent peak at 1414.29 cm^{-1} corresponds to the carbonate ion (CO_3^{2-}) stretching vibration, which is a sign of calcium carbonate presence. The peak at 873.47 cm^{-1} corresponds to the out-of-plane bending vibration of carbonate ions, and at 1056.34 cm^{-1} represents the in-plane bending vibration of carbonate ions. These results agree with previous FTIR studies on calcium carbonate materials (Féliz-Matos et al., 2015). The sharp bands around 3683.28 cm^{-1} and 3772.12 cm^{-1} indicate O–H stretching vibrations, which show the presence of water or hydroxyl groups in the eggshell matrix, which is typical of biological materials (Tizo et al., 2018). The absorption band at 3150.51 cm^{-1} also corresponds to O–H stretching because of adsorbed water on the calcined eggshell powder (Awogbemi et al., 2020). The weak band at 1959.76 cm^{-1} refers to the combination or overtone modes of carbonate (CO_3^{2-}) vibrations. And this indicates a small amount of residual $CaCO_3$ after calcination (Hani et al., 2025). Overall, the FTIR results confirm that the $CaCO_3$ are mainly found in eggshell powder with organic components such as proteins and other biomolecules. Thus, these findings are consistent with other studies on eggshell composition and demonstrate using FTIR for biomaterial characterisation.

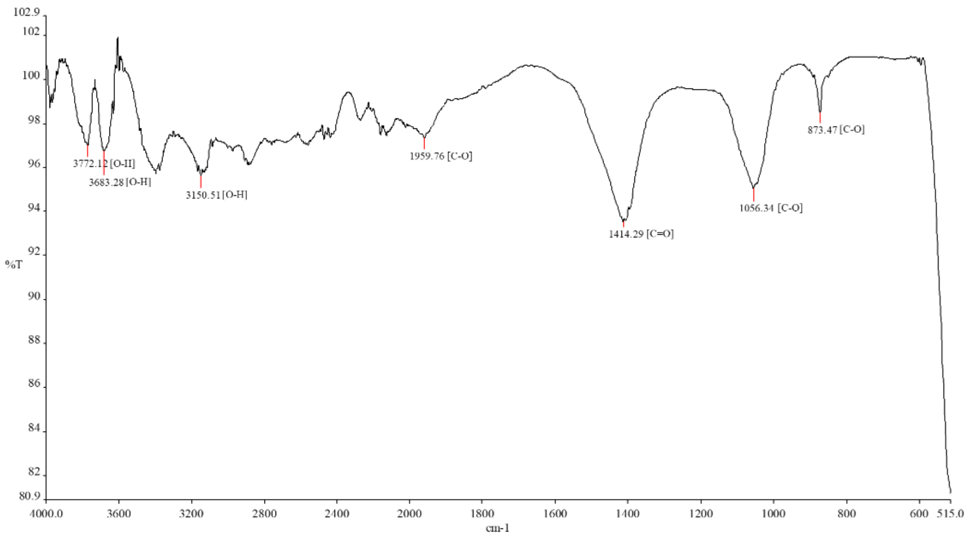

Fig. 3. FTIR results of calcinated eggshell powder

Source : Author's own data

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Analysis of x-ray diffraction (XRD)

Analysis of calcium carbonate content in eggshell powder was conducted using x-ray diffraction (XRD). The XRD data, as shown in Fig. 4, clearly indicate that the eggshell powder is composed of $CaCO_3$, with a peak appearing at 2θ = 29.48°. This peak is a characteristic feature of $CaCO_3$ and has been corroborated as the peak with the highest intensity (Bwatanglang et al., 2021). The intensity and sharpness of these peaks indicate that the calcium carbonate in the eggshell powder is well-crystallised. Such crystallinity is indicative of the aragonite form of $CaCO_3$, which is known for its crystalline structure. This observation is in line with the findings which also reported similar crystalline characteristics in $CaCO_3$ derived from eggshells (Bwatanglang et al., 2021)

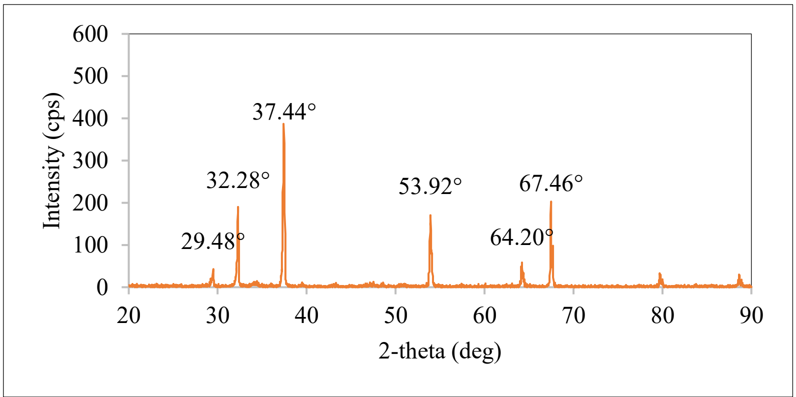

Fig. 4. XRD results for calcinated eggshell powder

Source: Authur's own data

X-ray diffraction (XRD) was conducted to analyse the $CaCO_3$ content for calcinated eggshell powder. Based on Fig. 4, the graph indicates that calcined eggshell powder is composed of $CaCO_3$, where a peak has appeared at 2θ = 29.48°. This peak is a characteristic feature of $CaCO_3$ and has been corroborated as the peak with the highest intensity (Bwatanglang et al., 2021). The sharp and intense peaks show that the calcium carbonate in the eggshell powder is well-crystallised. This crystallinity indicates the presence of the aragonite form of $CaCO_3$, which has a distinct crystalline structure. This observation is in line with the findings, which also reported similar crystalline characteristics in $CaCO_3$ derived from eggshells (Bwatanglang et al., 2021). This not only provides a sustainable approach to utilising waste materials but also offers an efficient means of obtaining high-purity calcium carbonate.

Analysis of x-ray fluorescence (XRF)

XRF analysis quantitatively measured the composition of calcined eggshell powder and eggshell-based toothpaste, and the result is reported in Table 2. Table 2 shows that eggshell-based toothpaste and eggshell powder have both similarities and differences in their element composition. They both contain high levels of calcium oxide (CaO) from calcium carbonate in eggshells, but eggshell powder has more CaO (97.32%) compared to eggshell toothpaste (93.51%), suggesting differences due to processing or mixing of additional ingredients in the toothpaste.

Both samples also contain sulphur trioxide (SO_3), with higher levels in the toothpaste (5.37%) than in the powder (1.36%), from added sulphate compounds for product enhancement. Trace amounts of other elements like magnesium oxide (MgO), aluminium oxide (Al_2O_3), and various oxides of metals and rare earths were found in both samples, contributing minimally to their composition.

Table 2. Composition of eggshell-based toothpaste and eggshell powder compounds from XRF

Compound	Eggshell-based toothpaste (%)	Calcined eggshell powder (%)
CaO	93.51	97.32
SO_3	5.37	1.36
MgO	0.40	0.90
Ag_2O	0.39	0.22
Al_2O_3	0.14	0.11
Cl	0.09	0.03
SrO	0.03	0.04
SnO_2	0.02	0.01
CuO	0.01	0.00
Lu_2O_3	0.01	0.00
Fe_2O_3	0.01	0.00
TeO_2	0.01	0.00

Source : Author's own data

3.2 Evaluation of the effectiveness of eggshell-based toothpaste

The abrasiveness of eggshell toothpaste

The potential of eggshells as an abrasive agent in toothpaste formulation can be qualitatively analysed with an abrasiveness test using aluminium foil. The result of abrasive test indicated that the toothpaste formulation had a slightly grainy texture due to the calcium carbonate particles. Fig. 5. shows an abrasion test in which the aluminium foil surface exhibited visible scratches after being rubbed with eggshell-based toothpaste.

a) b)

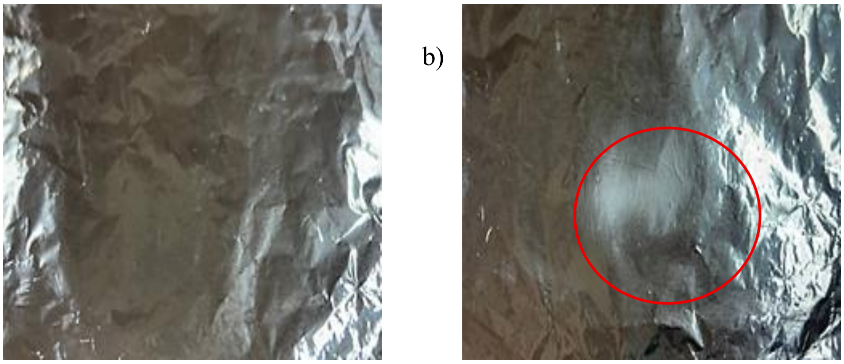

Fig. 5. Abrasion test on aluminium foil (a) blank aluminium foil (b) aluminium foil after being brushed with eggshell-based toothpaste

Source: Author's illustration

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Scratches observed on the aluminium foil indicate that the eggshell-based toothpaste is abrasive. The high abrasiveness might be due to the large particle size or high hardness of the eggshell powder. There is a good level of abrasiveness that helps clean the teeth, but too much abrasiveness may result in the abrasion of tooth enamel with time. This risk can be minimised by optimising the particle size and concentration of eggshell powder and ensure a successful cleaning (Cheng et al., 2020).

There must be further research aimed at improving the toothpaste formulation in terms of its long-term safety and performance. Eggshell-derived calcium carbonate is a natural abrasive, although excess of it may lead to enamel wear, tooth sensitivity, cavities and discolouration. To avoid this, the size of the particles should be selectively maintained. Keeping the pH near the neutral level will also serve to ensure that the enamel is not damaged.

pH analysis of eggshell-based toothpaste

The pH of toothpaste is a significant consideration when it comes to toothpaste formulation as it influences the stability of the product and its oral interactions (Gavic et al., 2018). The adjustment and pH test of the eggshell-based toothpaste were done thrice, and the results are presented in Table 3.

Table 3. pH test result on eggshell-based toothpaste

Test	pH value
1	7.55
2	7.98
3	8.78

Source: Author's own data

The average pH value for eggshell-based toothpaste is pH 8.05, which falls within an alkali range, which is safe for oral health. This is important because an alkali pH can ensure that the toothpaste will not cause enamel erosion or irritation of the oral mucosa. The consistent pH readings in multiple trials show that the formulation is stable and reliable. This pH also aligns with findings that emphasised the importance of pH in maintaining the efficacy and safety of toothpaste (Shiferaw et al., 2019

Foaming test for eggshell-based toothpaste

The foaming effect in toothpaste is significant to the user perception to feel that the toothpaste is clean and covers the teeth. Thus, foaming tests were performed for eggshell-based toothpaste and compared with commercial toothpaste. The foaming test results in Fig. 6 indicate that the eggshell-based toothpaste generated a higher foam height (14 mL) compared to commercial toothpaste (12 mL).

The foaming tendency that is increased in the eggshell-based toothpaste formulations has a considerable effect on consumer experience. Foam is often associated with effective cleaning action because it helps to distribute the paste on the teeth and gums evenly (Chugh et al., 2024). High foam is perceived by consumers as an indicator of high cleansing efficacy, and, thus, it adds to a more refreshing and enjoyable brushing experience (Paissoni et al., 2023). It is especially relevant to the oral products where the equal qualities can influence the user preferences and the acceptance of the product. Improved foam production could increase the time of brushing, hence further improving the dental health results. On the other hand, the amount of

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foam formed can be so large as to threaten the stability of the entire formulation (Polyakova et al., 2024). This foaming effect is increased with the help of surfactants like sodium lauryl sulphate (SLS) which can modify the viscosity and long-term consistency of the product. These modifications can increase the rate of active constituents, reducing their effectiveness with prolonged use. Therefore, the balance of the foam produced with the stability of ingredients should be within an optimum condition, to ensure the effectiveness of the toothpaste. Further investigation on the rheological and foaming properties over time is necessary for optimising both consumer satisfaction and product performance (Abou Neel & Bakhsh, 2021).

Eggshell-based materials are deemed safe to use in the mouth due to the natural occurrence of calcium carbonate and trace mineral mix composition. In empirical research, it was found that eggshell powders may become safe, biocompatible, and void of harmful pathogens through appropriate treatment of heat or calcifying, cleaning, and sterilisation (Shiferaw et al., 2019). Besides, the calcium derived from eggshells has been recognised as approved both biomedically and pharmaceutically, thus reaffirming its suitability in toothpaste preparations. Therefore, the usage of eggshell powder not only ensures sustainability but also protects the safety of consumers.

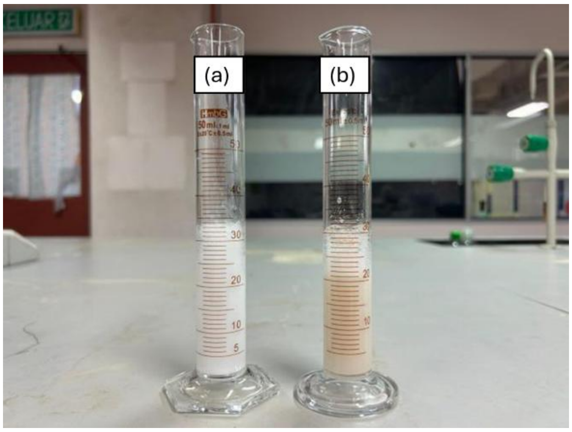

Fig. 6. Different between foaming height observed in (a) commercial toothpaste and (b) eggshell-based toothpaste

Source: Author's illustration

4. CONCLUSION

In conclusion, this paper has clearly established that it is possible to incorporate eggshell powder as a sustainable alternative ingredient in toothpaste formulations. The FTIR, XRD and XRF characterisation of the calcined eggshell powder proves that the main constituent of the material is calcium carbonate ($CaCO_3$). The characteristically carbonate bands were also observed in the FTIR spectrum at 1414.29 cm^{-1}, 1056.34 cm^{-1} and 873.47 cm^{-1}, validating the presence of CO_3^{2-} groups. Further, XRD analysis confirmed these results with a major diffraction peak occurring at $2\theta = 29.48°$ indicative of well-crystallised aragonite-phase $CaCO_3$. XRF analysis showed that CaO was the dominant oxide (97.32% and 93.51% for the calcined

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powder and eggshell-based toothpaste, respectively). Collectively, these characterisations support the use of the calcined eggshell as a calcium-rich crystalline biomaterial with $CaCO_3$ and CaO-dominated phases, and a promising sustainable source for bio-derived filler for material applications.

The performance of eggshell-based toothpaste evaluation shows that it has good cleaning performance, a reasonable pH, and satisfactory foaming. From the results of the abrasiveness test, calcium carbonate from eggshells proved to be a good and effective natural abrasive agent; nevertheless, the calcium carbonate particle size should be optimised to prevent enamel wear. The pH measurement of 8.05 shows that the formulation is alkaline and therefore stable and safe for oral administration. In addition, the toothpaste had a greater foaming capacity than commercial preparations and thus, it may lead to improved user satisfaction and functional efficiency. Overall, the eggshell-derived formulation has shown favourable characteristics as a natural and sustainable oral-care product, still more that needs to be improved with regards to abrasiveness, foaming and stability over time.

The research in the future should focus on finding the optimal particle size of eggshell powder to achieve a good balance between abrasiveness and the safety of enamel. Furthermore, the addition of adjunctive agents (i.e., herbal extracts or remineralising additives) can have a positive impact on the creation of this new formulation. It is also important to explore the potential long-term effects of using eggshell-based toothpaste through in vivo studies by assessing their safety and effectiveness for actual oral care. These directions can enhance the toothpaste formulation and broaden its commercialisation prospect as a sustainable and natural dental care product.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no financial, professional, or personal interests that could be construed as influencing the content, results, or interpretations presented in this research.

AUTHORS' CONTRIBUTIONS

Nur Azurah Zuraikha Binti Mohd Zulkarnain: Methodology establishment, Experiments & Manuscript Writing. **Harumi Veny**: Research grant acquisition, Methodology & experiments establishment, Supervision, Manuscript Writing & Editing. **Farah Hanim Ab Hamid**: Manuscript writing & Editing. **Rozana Azrina Sazali**: Manuscript writing & Paraphrasing. **Sri Rizki Putri Primandani**: Manuscript writing & Editing. **Zulkifli Abd Rashid**: Manuscript writing & Editing. **Azil Bahari Alias**: Manuscript writing & Editing.

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